



The Onset of the Cataclysm: ***In situ* dating of a nearside basin impact-melt sheet** ***or, there and not back again***

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Lunar Science for Landed Missions
Workshop





A Lunar Cataclysm...?

- ★ Impact-melt samples from Apollo & Luna are 3.85-4.1 Ga, tied to Imbrium, Serenitatis, Crisium, Nectaris, plus other craters?
- ★ May have been caused by destabilization of material in early Solar System by dynamic forces such as gas drag and gravitational interactions
- ★ Coincident with the oldest rocks on the Earth and *later* than the earliest isotopic signs of life on Earth – Earth was already a planet with oceans, plate tectonics, and single-celled life
- ★ **What was happening on the Moon before 3.9 Ga affected the course of life on Earth, the structure of our Solar System, and the dynamics of extrasolar planetary systems**

But wait. What if there was no cataclysm?



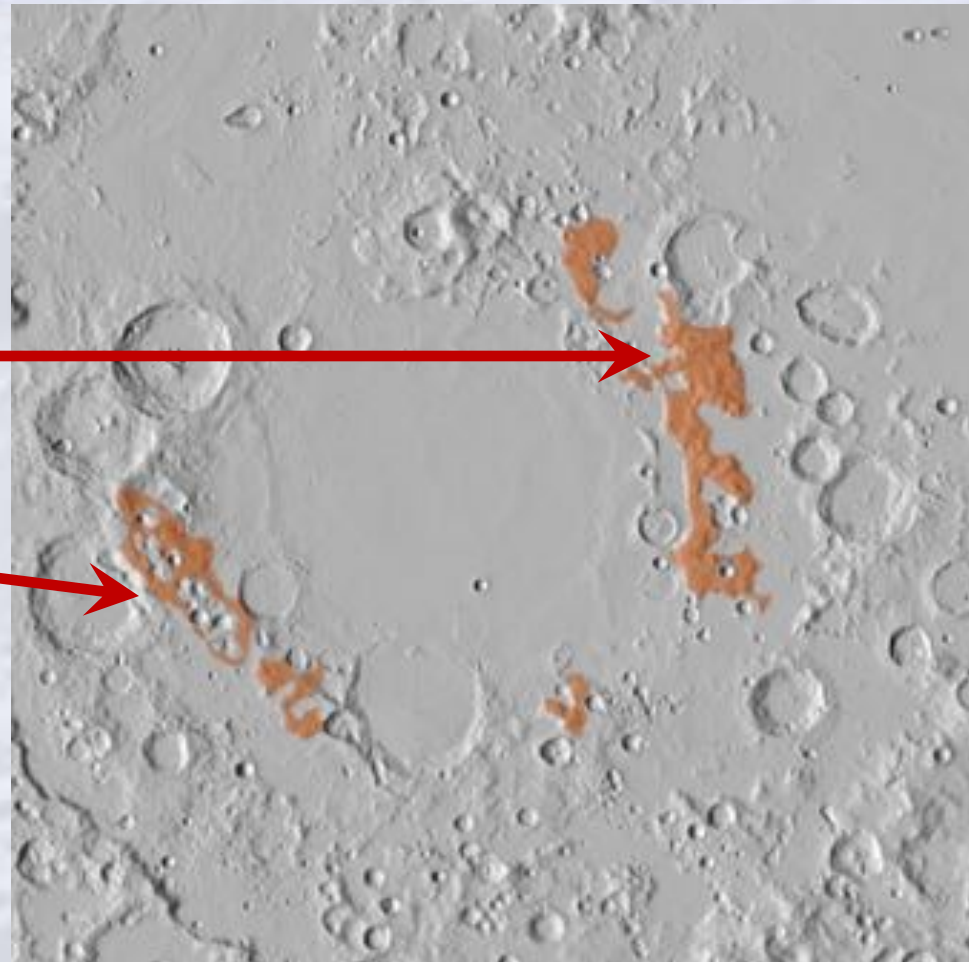
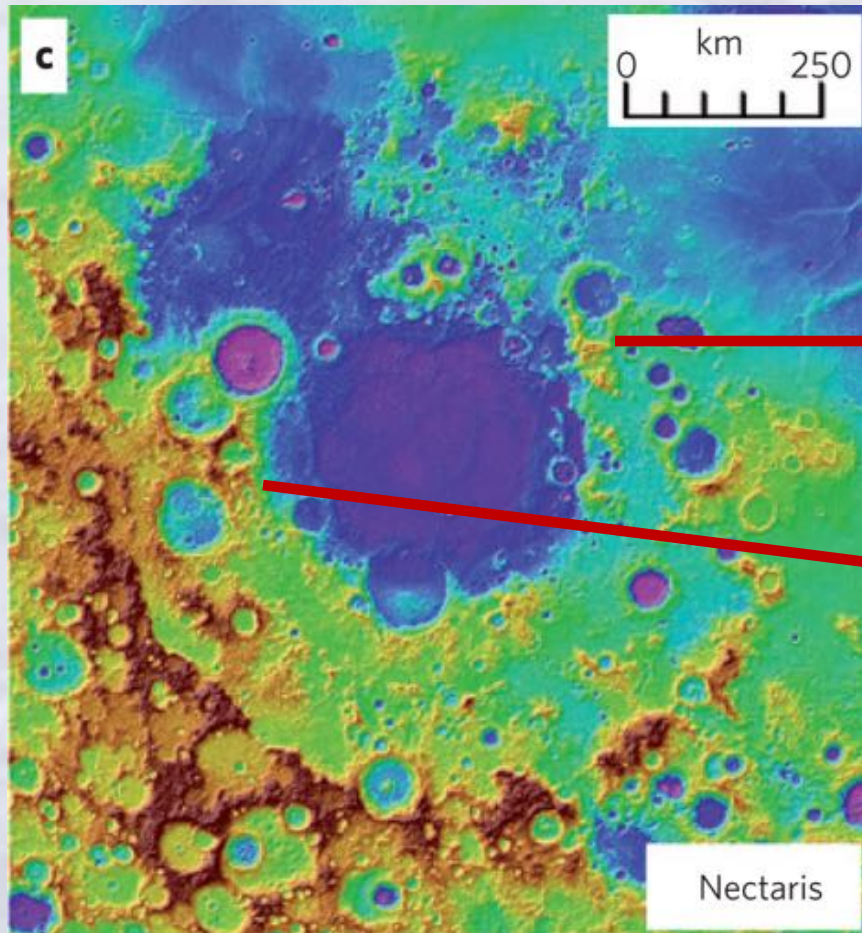
- ★ Ongoing work on samples in the last decade, presented at Solar System Bombardment workshops in 2008, 2012, 2015
- ★ What we thought were Serenitatis impact-melt rocks actually have strong affinity to Imbrium samples, and their origin in the Descartes Fm has been geologically linked to Imbrium. Oops.
- ★ Crisium samples from Luna 20 are small and discordant, no agreement on whether they are impact melt.
- ★ Impact-melt samples from Apollo 16 give ages for Nectaris from 3.85 Ga-4.2 Ga depending on who interprets them – no agreement on what is from Nectaris. Oops.
- ★ **Samples thrown from basins don't come tagged with their origin. Norman (2009) called this "Pulling the pin" on the start of the Cataclysm!**



So, how can we resolve this?

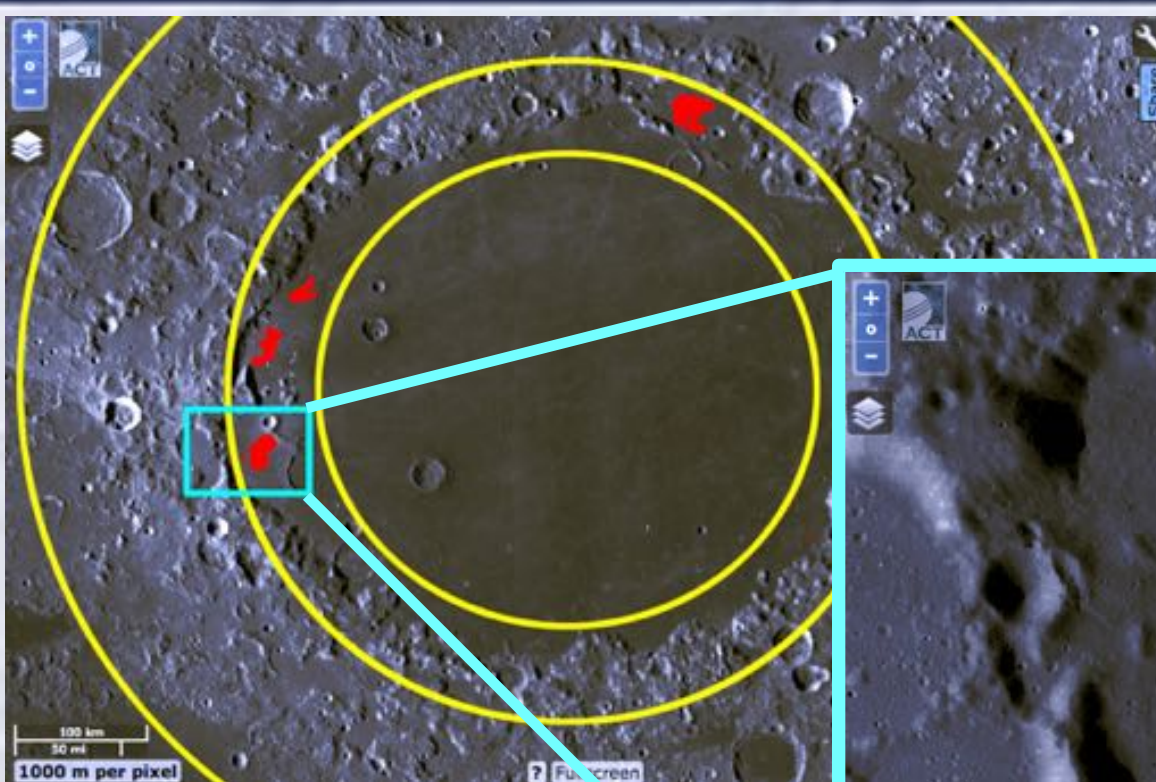
- ✦ Date the melt sheet of a well-known, pre-Imbrian basin(s)!
- ✦ **South Pole – Aitken Basin** is far from Imbrium, records impact history since its formation (including Apollo, Ingenii, Poincare)
 - New Frontiers class mission – farside, comsat, sample return
- ✦ Near side basins generally have mare covering their impact-melt sheets, but impact-melt kipukas may have been identified!
- ✦ **Nectaris** is a stratigraphic horizon - the Nectarian Epoch defines the onset of the cataclysm
- ✦ **Crisium** is also pre-Imbrian and may also have promising sites

Nectaris in-place impact melt identified



- ★ Small plains near inner basin ring massifs and intermassif “draped” deposits mapped as Nectaris basin impact melt sheet remnants (Spudis and Smith 2013)

Crisium in-place impact melt identified



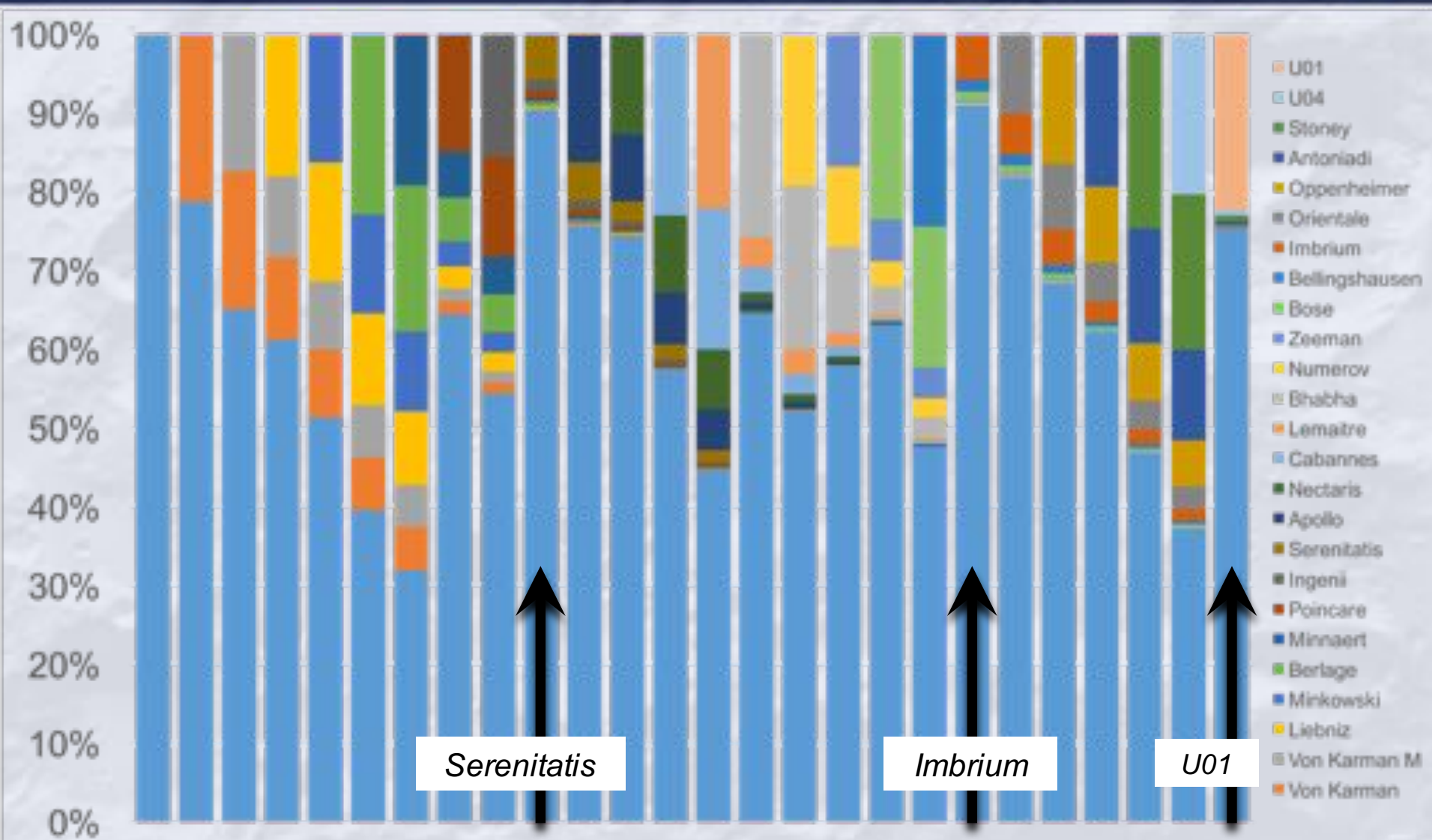
- ★ Low FeO, cracked texture, higher crater density (Spudis & Sliz 2017)

Regolith scoop sampling

- ★ Much of the present debate about the ages of the nearside basins arises because of the difficulty in understanding the relationship of distal samples to their parent basin
- ★ **Melt sheets are a fundamentally different geologic setting than the Apollo sites**
- ★ Regolith formed on the basin impact-melt substrate, diluting but not destroying native impact-melt rocks
- ★ Geochemical signatures are evident from orbit
- ★ 1% of the lunar regolith is rocklets 1-3 cm; need a scoop/sieve strategy (well-developed for MoonRise)



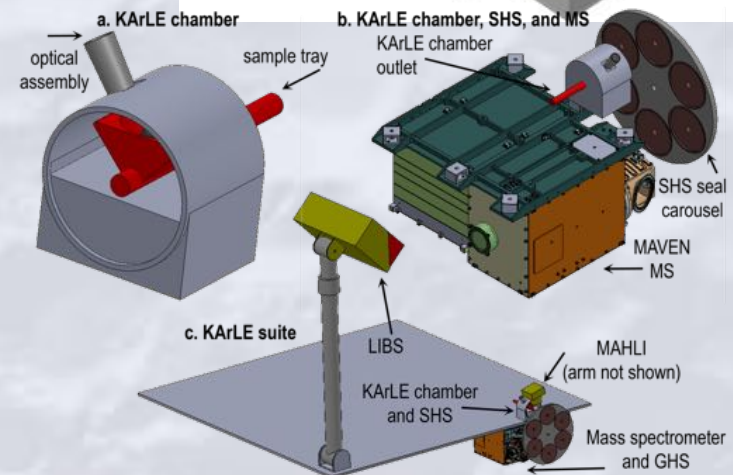
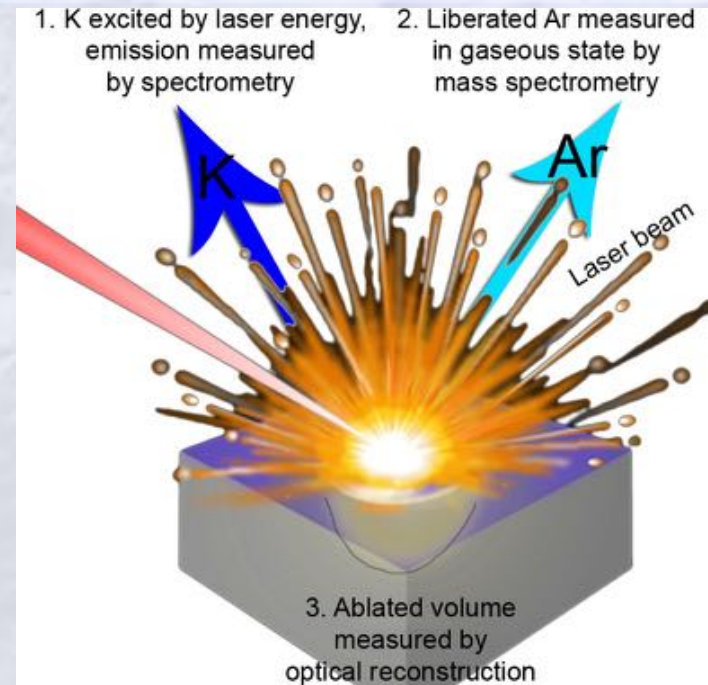
Regolith scoop sampling



Proportion of material from different craters in the upper 1 m at Bhabha site in SPA

K-Ar Geochronology using LIBS-MS

- ★ K measured using laser-induced breakdown spectroscopy (e.g. Chemcam), also ablates the rock
- ★ Liberated Ar measured using mass spectrometry (e.g. MAVEN-MS)
- ★ K and Ar related by volume of the ablated pit using optical measurement (e.g. MAHLI)
- ★ All TRL 9 instruments – low risk, known cost
- ★ Instruments do double duty – complete composition, petrology, volatiles
- ★ Conops fits with real mission flight ops
- ★ Precision $\pm 100\text{-}150$ Myr for a 4 Ga sample





Baseline Science Payload (~35 kg)

Mission Element	Objective	Heritage	Mass (kg)	Power (W)
Sample collection & delivery mechanism	<ul style="list-style-type: none"> Scoop & sieve / rake regolith Present rocks to MIBS and MI for triage Introduce individual rocks to analysis chamber 	Apollo, MoonRise	20	tbd
LIBS	<ul style="list-style-type: none"> Survey landing site materials (active and passive) Characterize and prioritize samples Determine K for geochronology Look for H siting 	ChemCam (MSL), SuperCam (Mars 2020)	10	65
Mass Spectrometer	<ul style="list-style-type: none"> Determine Ar for geochronology Measure other volatile compounds and their isotopic composition 	NGMS flown on MAVEN, MSL, etc.	5	40
Microscopic imager	<ul style="list-style-type: none"> Workspace documentation Characterize and prioritize samples Measurements of LIBS pits for geochronology 	MER MI, MSL MAHLI, MSSS Hawkeye	1 (for 2)	4
Possible: LIDAR	<ul style="list-style-type: none"> Descent support Workspace definition 			

Dedicated Science Instrument (~14 kg)



Mission Element	Objective	Heritage	Mass (kg)	Power (W)
Sample collection & delivery mechanism	<ul style="list-style-type: none"> Introduce sample to analysis chamber 	Microsampler/ pencil corer/rake	3	tbd
LIBS	<ul style="list-style-type: none"> Determine K for geochronology 	Part of ChemCam (MSL) at fixed focus on sample	5	55
Mass Spectrometer	<ul style="list-style-type: none"> Determine Ar for geochronology 	NGMS flown on MAVEN, MSL, etc.	5	40
Microscopic imager	<ul style="list-style-type: none"> Measurements of LIBS pits for geochronology 	MER MI, MSL MAHLI, MSSS Hawkeye	0.5	2

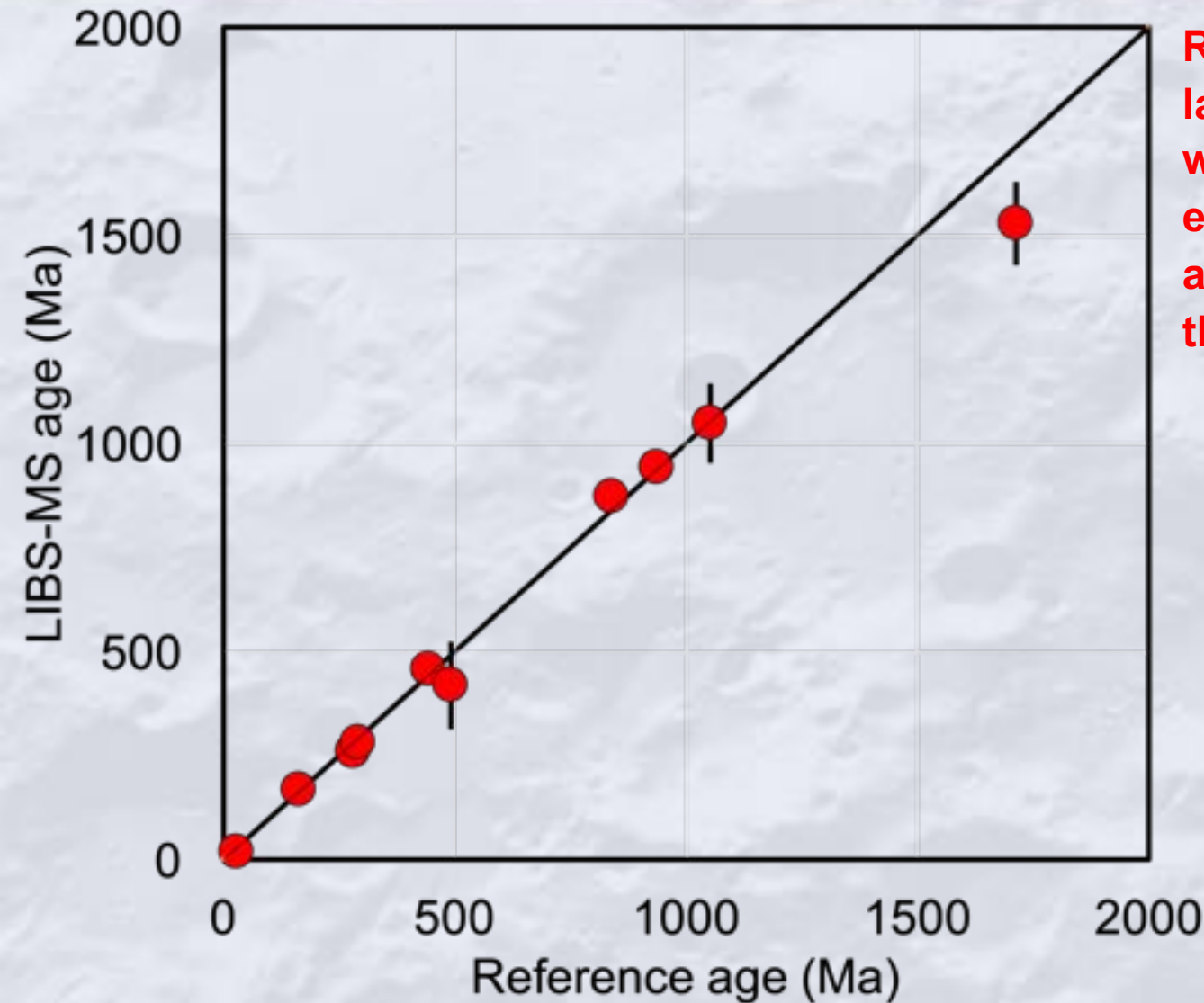


Pathfinder option (~10 kg)

Mission Element	Objective	Heritage	Mass (kg)	Power (W)
LIBS	<ul style="list-style-type: none">• Fixed focus from deck straight down• Look for H siting	ChemCam (MSL)	5	55
Mass Spectrometer	<ul style="list-style-type: none">• Open to laser ablation site on ground• Measure released volatiles from laser ablation	NGMS flown on MAVEN, MSL, etc.	5	40



K-Ar Geochronology using LIBS-MS



Results from multiple laboratories yield whole-rock ages within error of accepted ages and precision close to theoretical = TRL 4

Solé (2014) Chemical Geology 388, p. 9-22; Cohen et al. (2014) Geostandards and Geoanalytical Research, doi: 10.1111/j.1751-908X.2014.00319.x;

Devismes et al. (2016) Geostandards and Geoanalytical Research, doi: 10.1111/ggr.12118; Cho et al. (2016) Planetary and Space Science 128, 14-29



Basin *in situ* dating mission

- ✦ Accomplishes solar-system wide science by visiting a stratigraphically important lunar basin
 - *In situ* geochronology
 - Sample and site characterization

- ✦ Accomplishes three of the four major goals of the SPA New Frontiers mission recommended in the Decadal Survey by conducting *in situ* dating rather than sample return
 - Single lander, no mobility
 - Nearside, subequatorial site
 - Extensively covered by LRO imaging

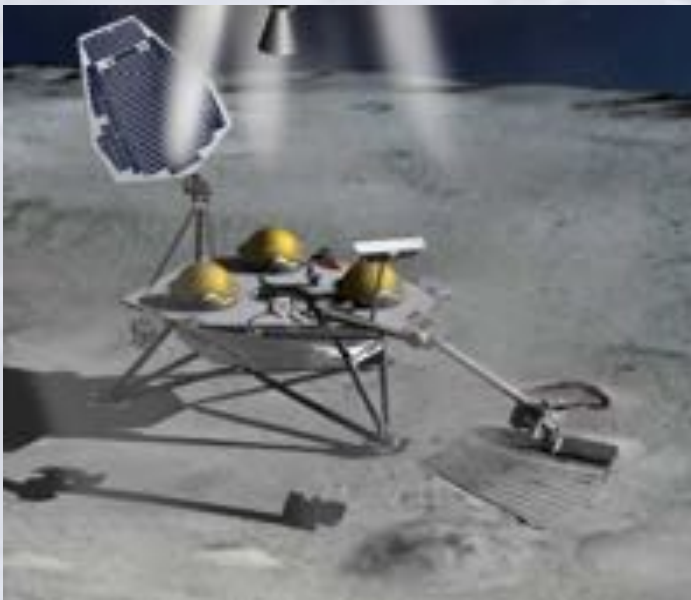
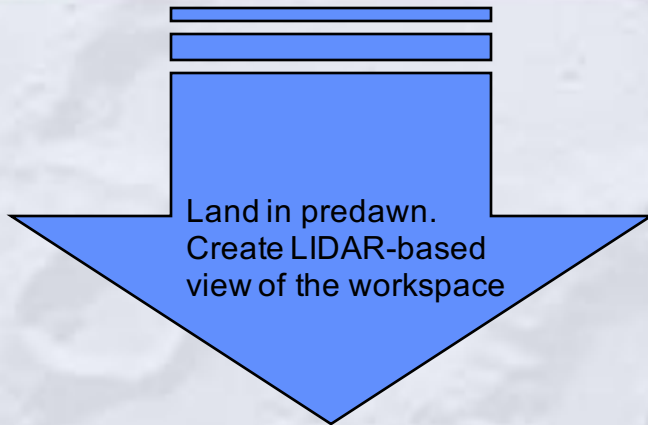
- ✦ Advances NASA investments in development of *in situ* geochronology measurements and science

Science Goals *from Decadal Survey*



- ✦ *Determine the chronology of basin-forming impacts and constrain the period of late heavy bombardment in the inner solar system and thus address fundamental questions of inner solar system impact processes and chronology*
 - Measure the K-Ar age of the Nectaris/Crisium basin impact-melt sheet (10-20 samples) and also KREEPy materials thrown far from the Imbrium basin (2-4 samples)
- ✦ *Determine age and compositions of basalts to determine how mantle source regions differ from regions sampled by Apollo and Luna*
 - Measure the age and composition of Mare Nectaris/Mare Crisium basalt (2-4 samples)
- ✦ *Characterize a large lunar impact basin through "ground truth" validation of global, regional, and local remotely sensed data of the sampled site*
 - Landing site characterization to correlate with orbital datasets
 - Measure the composition & petrology of samples at a site remote from the Apollo and Luna landing sites to understand their origin

Notional Conops



Scoop and sieve operations to collect rocks from the regolith

